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Level and length of cyclic solar activity during the Maunder minimum as deduced from the active day statistics

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ABSTRACT

Aims. The Maunder minimum (MM) of greatly reduced solar activity took place in 1645–1715, but the exact level of sunspot activity is uncertain as based, to a large extent, on historical generic statements of the absence of spots on the Sun. Here we aim, using a conservative approach, to assess the level and length of solar cycle during the Maunder minimum, on the basis of direct historical records by astronomers of that time.
Methods. A database of the active and inactive days (days with and without recorded sunspots on the solar disc respectively) is constructed for three models of different levels of conservatism (loose ML, optimum MO and strict MS models) regarding generic no-spot records. We have used the active day fraction to estimate the group sunspot number during the MM.
Results. A clear cyclic variability is found throughout the MM with peaks at around 1655–1657, 1675, 1684 and 1705, and possibly 1666, with the active day fraction not exceeding 0.2, 0.3 or 0.4 during the core MM, for the three models. Estimated sunspot numbers are found very low in accordance with a grand minimum of solar activity.
Conclusions. We have found, for the core MM (1650-1700), that: (1) A large fraction of no-spot records, corresponding to the solar meridian observations, may be unreliable in the conventional database. (2) The active day fraction remained low (below 0.3–0.4) throughout the MM, indicating the low level of sunspot activity. (3) The solar cycle appears clearly during the core MM. (4) The length of the solar cycle during the core MM appears 9 ± 1 years, but there is an uncertainty in that. (5) The magnitude of the sunspot cycle during MM is assessed to be below 5–10 in sunspot numbers; A hypothesis of the high solar cycles during the MM is not confirmed.

Key words. Sun:activity - Sun:dynamo - Sun:Maunder Minimum

1. Introduction

There was a period, in the second part of the 17th century, of greatly reduced solar activity that was named the Maunder Minimum (MM) by Eddy (1976). The MM was characterized by almost complete absence of reported sunspots on the solar surface although some indications of cyclic activity can be noticed particularly in the geomagnetic and heliospheric indices (Beer et al. 1998; Usoskin et al. 2001; Soon & Yaskell 2003). The reconstruction of solar activity based on the historical records of telescopic observations of sunspots since 1610 (Hoyt & Schatten 1998a; Hoyt & Schatten 1998b, – called HS98 henceforth) marked a milestone in the study of solar activity in the recent past and, especially, for the MM period. The Group Sunspot Number (GSN) built by HS98 became the only high-resolution (daily) index to study solar activity during the MM.

The aim of this work is to elucidate whether the absence of the sunspot cyclic activity during the MM was real or an artefact caused by a problem of compilation of the database of sunspot records. Several studies pointed to possible inconsistences in the database used by HS98 especially around the MM (e.g., Vaquero & Vázquez 2009; Vaquero et al. 2011; Vaquero & Trigo 2014). As an extreme, Zolotova & Ponyavin (2015) claimed there was no grand Maunder minimum and that sunspot cycles during MM were as high as $\approx$ 100, which is higher than the current cycle # 24. We note that the MM is well covered by sunspot data and more than 90% of days have formal observation records in the HS98 database. However, it contains a large number of generic statements of the absence of sunspots during a long period of time. Such records are not strict observational data but they were interpreted by HS98 as no-spot data. Many of these records corresponded to solar meridian observations (Vaquero 2007; Clette et al. 2014) and should be used with caution for the reconstruction of solar activity, as shown by Vaquero et al. (2014) who analyzed sunspot records taken during systematic solar meridian observations performed at the Royal Observatory of the Spanish Navy from 1833 to 1840. Moreover, as Carrasco et al. (2015) suggested basing on an analysis of sunspot records by Hevelius in the 17th century, the GSN index may be underestimated during the MM due to a large number of "zero" sunspot records taken from solar meridian observations. In general, astrometric observations of the Sun are not always reliable for sunspot counting because of the different aim of such observations. For example, there is no information on sunspots in the extensive table of astrometric records of the Sun made with the meridian line in the San Petronio Basilica from 1645 to 1735 as published by Manfredi (1736). Nevertheless, Hoyt & Schatten (1998a) adopted solar observations recorded in this source as no-spot reports, which is not correct. It has been discussed that, while the definition of sunspot numbers and even sunspot groups is not very reliable in the earlier part of the GSN series (Clette et al. 2014; Zolotova & Ponyavin 2015), solar activity during the MM can be reliably represented by the fraction

of active days (Kovaltsov et al. 2004; Vaquero et al. 2012, 2014; Usoskin 2013).

Despite the overall level of activity, the parameters of the solar cyclic variability during MM are also important to know. Although the solar cycle was perceptible in the butterfly diagram (Ribes & Nesme-Ribes 1993; Vaquero et al. 2015) based on the observations of sunspot latitudes during the last decades of the 17th century, the 11-year solar cycle is only marginally detectable in the sunspot numbers (Waldmeier 1961; Mendoza 1997) with a weak 22-year cycle dominated (Usoskin et al. 2001). On the other hand, some works based on data of high-resolution cosmogenic ^{14}C measured in tree trunks suggest that the solar cycle might have been stretched during Grand solar minima (Stuiver et al. 1998; Miyahara et al. 2004; Miyahara et al. 2006; Miyahara et al. 2010; Nagaya et al. 2012; Miyake et al. 2013). These studies have suggested that the length of the solar cycle was increased to about 14 years during the MM, to about 13 years in the beginning of the Spörer Minimum, up to 16 years during the 4th Century BC Minimum, and to 12–13 years during the late 7th century minima.

In this work we aim to study variability of solar activity during the MM using the statistics of the active days basing on only the most reliable solar observations from the database compiled by Hoyt & Schatten (1998a) and to establish an uppermost upper (*maximum maximorum*) limit on that.

2. Sunspot activity database

Since quantitative interpretation of many records is uncertain for that period, we consider only qualitative indicators of the sunspot activity for each day for the period 1637–1715 AD. Leaving aside the exact number of reported sunspot group in the HS98 catalog, we only consider three possible states for each day:

– no-information or missing days;
– inactive days when we believe there were reliable observation of the absence of sunspots;
– active days when at least one sunspot group was explicitly reported by at least one observer;

We build our database of the active and inactive days for three models of different levels of conservatism regarding generic no-spot records. For the period 1637–1642, we used exactly the records listed by Vaquero et al. (2011). For the period 1643–1715, we used the records from the HS98 database (http://www.ngdc.noaa.gov/stp/sunspot_numbers/group_sunspot_numbers/alldata.dat) for each observer separately. In addition, for the year 1672 several active days were added according to observations by N. Bion not included into the HS98 database (Casas et al. 2006). While the original HS98 database contains 26508 daily records for the analyzed period 1637–1715, our models include much less records because of rejecting, with different levels of conservatism, generic statement mostly related to no-spot observations. All these models provide an overestimated upper bound of sunspot activity due to a possible selection bias towards active days.

2.1. Loose model (ML)

This model is similar to that by Kovaltsov et al. (2004) and ignores all the generic statements (longer than a month) in the HS98 database, and considers only explicit statements with exact mentioning dates of observations. This affects such generic statements as, e.g., by J. Hevelius for no spots during 1645–1651, by J. Picard for 1653–1665, by H. Siverius for 1675-1689, etc. This model is least conservative and is called ”loose”. It includes 13512 observational days which is nearly half of the HS98 database.

2.2. Optimum model (MO)

The MO model provides a reasonable balance between strictness and data acceptance and is considered as the optimum conservative. For each year, we considered observations of only those observers who reported at least one sunspot group at any day of the year, which would prove that the observer was ”active”. In this way, generic long-extending reports of ”no-spot” were neglected but no-spot records of active observers were considered. The MO models is biased towards ”active” years and produces no result for the years without sunspot observations. For example, if a year is full of definite ”no-spot” records but does not contain a single sunspot observation reported, such year is marked as ”no-information” in this model. Alternatively, if an observer was ”active” during a year, his generic ”no-spot” records for this year were considered by the model, so that the total number of days N_T in the MO model may exceed that for the ML model for some years (see Fig. 1). This model includes 8089 observational days for the period analyzed, which is roughly $^1/_3$ of the full HS98 database.

2.3. Strict model (MS)

In this ”strict” model we excluded all the generic statements as in the ML models, but additionally we treated other no-spot records in a very conservative way, so that we consider as inactive only days, when at least two observers independently reported that the Sun was spotless and there were no other records of sunspots. If at least one observer reported sunspots, the day was considered as active. All other days were treated as no-information days. This is the most conservative approach, especially in the earlier part of the Maunder minimum, when the number of documented observers was low and they rarely overlap. This model includes 5159 daily records or $^1/_5$ of the full HS98 database.

For each model we define the number of active N_A and the total number N_T of the accepted observational days in a year. Since the annual data are quite noisy (see below) we also consider triennial intervals. In order to keep the strictness, the MO model was still operating with annual periods to identify ”active” observers. The results are shown in Fig. 1 for the three models as well as for the formal HS98 database. One can see that, while the HS98 database covers the entire period pretty well, the three models provide a more conservative estimate of reliable observations, which is greatly reduced in the earlier Maunder minimum but is quite solid towards its end.

An example of the coverage of the data in the three models and the formal HS98 database is shown in Fig. 2 for the year 1676. Although this year was almost fully covered by data in the formal HS98 database, except for a short gap in October, the three models considered here include much less inactive days while keeping the active days. A small discrepancy in the number of active days is related to excluded interpolations (as in Dec 22–24) and confusing values (as in Jun 25 when a sunspot record by R. Hook was missed in the formal HS98 series) in the HS98 database.

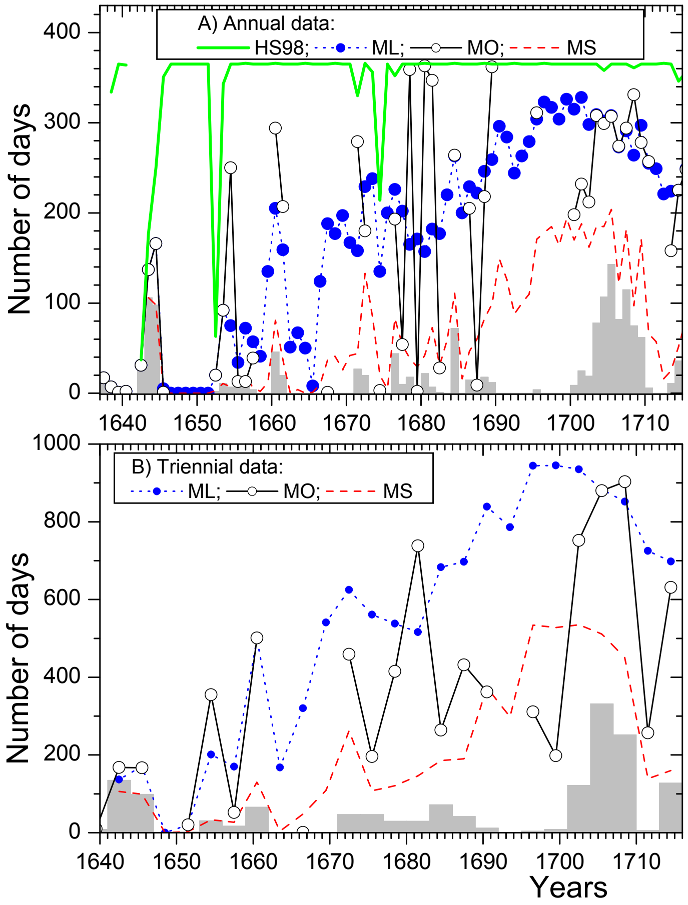

Fig. 1. The number of active days N_A (grey bars) and total observational days N_T (curves as defined in the legend for the three models and the formal HS98 database) per interval used. Panels A and B depict annual and triennial data, respectively.

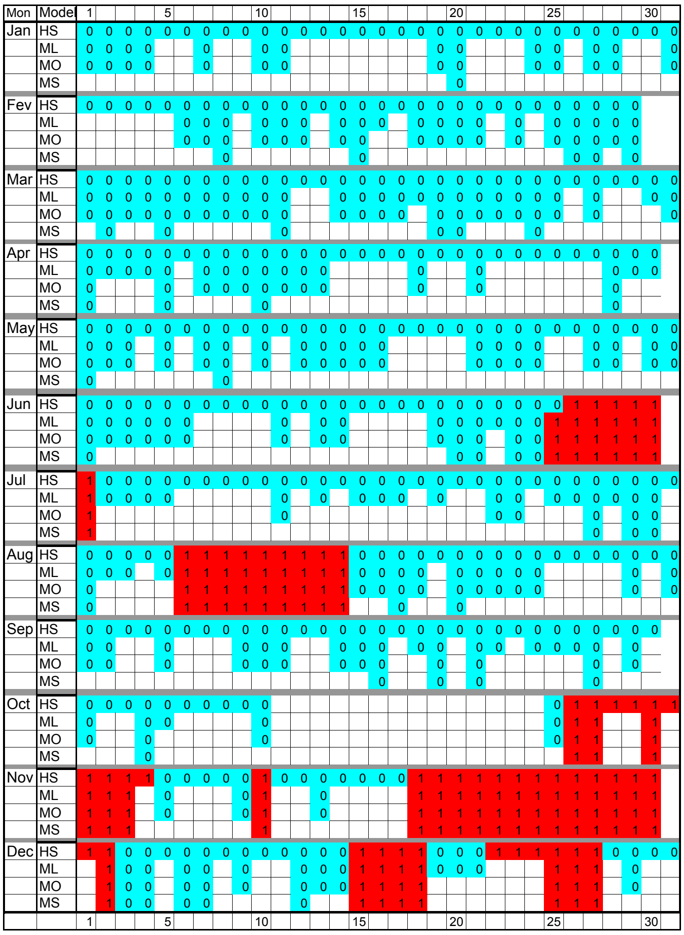

Fig. 2. A map of the days allocation for the year 1676 in the original HS98 database (denoted as HS) and the three models considered here. Each line represents one month (days of the month numbered on the top and bottom) for a model. The empty white, blue "0" and red "1" cells correspond to no-information, no-spot and active days.

We emphasize again that the procedure described above serves as an uppermost upper bound because of possible over-suppressing zero-sunspot records.

3. Results

3.1. Active day fraction

From the collected database of sunspot records, we have estimated the fraction of active days F_A in each model, as follows (cf. Kovaltsov et al. 2004). For each interval, either annual or triennial, we have a sample of n daily observations with r active days reported. Assuming these observation were taken randomly and independently, one can assess the probability of the occurrence of exactly s active days within N days during the considered interval (a year or 3 years) using the hypergeometric probability distribution:

$$p(s) = \frac{s!\,(N-s)!}{(s-r)!\,(N-s-n+r)!} \cdot \frac{n!\,(N-n)!}{(n-r)!\,N!\,r!} \qquad (1)$$

As the optimum value of $s*$ we consider the median value, viz. the value of s which yields $P(s*) \equiv \sum_r^{s*} p(s) = 0.5$. The results for annual and triennial time intervals are shown, along with error bars of a 90% (two-sided) confidence interval, in Figures 3 and 4, respectively. We note that triennial data were calculated from the original daily values using equation (1) and not as an average of the annual data.

3.2. Length of solar cycles

Although the annual data are quite noisy, the triennial ones (see Table 1) clearly show a decadal periodicity during the MM. For example, Figure 4 suggests maxima of solar cycles around 1639, 1655–1657, 1675, 1684 and 1705 in all the models. There is also an indication of a cycle maximum around 1666 in the MO models, but the statistics is low with a single observation for the 3-year interval. Periods around 1648 and 1693 are poorly known with data gaps in the MO model.

There are four solar activity maxima in the core MM, between maxima ca. 1657 and 1684. This leads to an estimate of the average solar cycle length (max-to-max) during the core MM as 9 ± 1 years. However, our view of the cyclic evolution of sunspot activity during MM is uncertain because of the unclear situation around 1648, 1666, and 1693. If we assume two hypothetical missing solar maxima during these periods, as e.g., Waldmeier (1961) proposed a cycle maximum in 1649, while Usoskin et al. (2001) suggested a maximum ca. 1695, we can estimate an average solar cycle length around the MM (from 1636 to 1711) to be 9.5 ± 0.5 years. If however, we assume that there were no additional solar cycle maxima around 1648 and 1693, the average cycle length (max-to-max) would be 13.2 ± 0.6

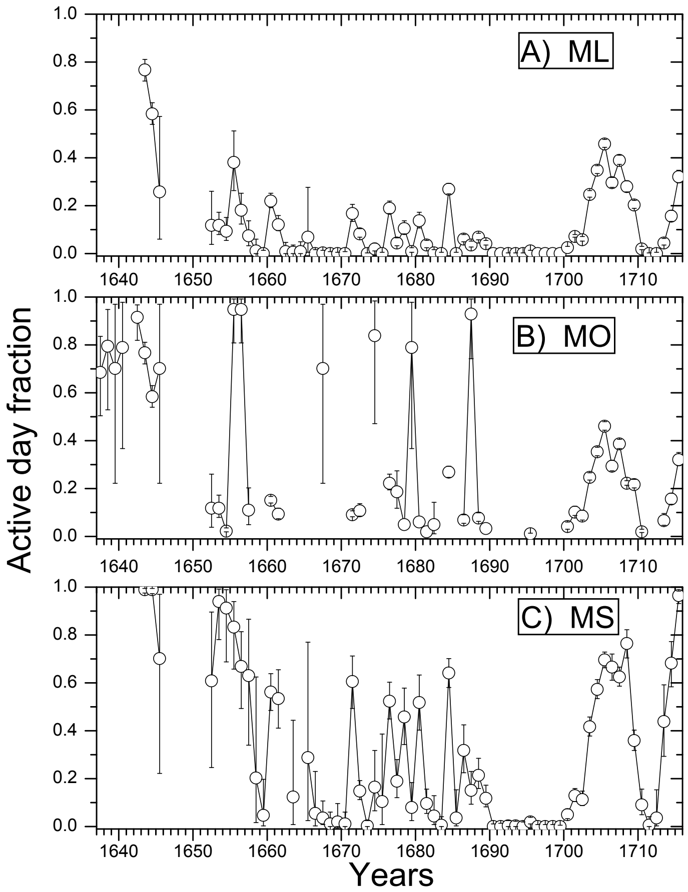

Fig. 3. Annual active day fraction for the three models. Error bars represent the 90% two-sided uncertainties.

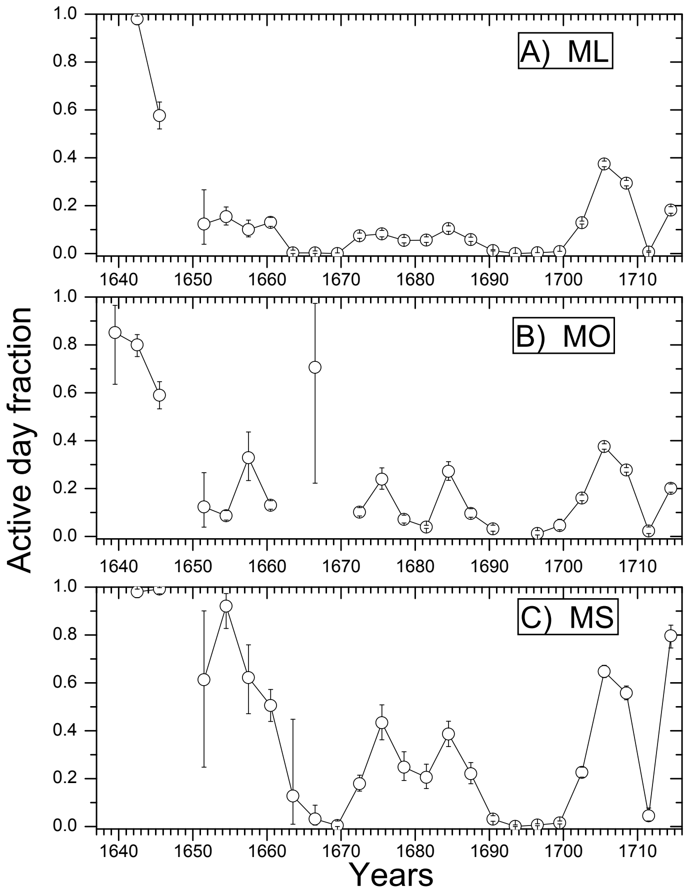

Fig. 4. Triennial active day fraction for the three models. Error bars represent the 90% two-sided uncertainties. Digital data is available in Table 1.

years. However in this case, the length of individual cycles varies greatly, between 9 and 18 years. The estimated cycle length is similar to but somewhat shorter than the results proposed by Mendoza (1997) and Usoskin et al. (2001) who suggested the cycle length of 10.5-11 years during the MM using sunspot observations. Meanwhile, clustering of activity in $\approx 20-$year intervals (1650–1670, 1670–1690, and 1690–1710) is also visible, in agreement with earlier results of the dominant 22-year periodicity during the MM (Usoskin et al. 2001). Note, however, that this clustering of activity could be also produced because of the scarcity of reliable data around 1648, 1669, and 1693.

On the other hand, estimates of the cycle length based on cosmogenic ^{14}C data suggest much longer cycles during Grand minima (13-16 years). We note however that ^{14}C data cannot resolve individual cycles, because of the global carbon cycle attenuating high-frequency variability (Roth & Joos 2013), but rather yields the mean periodicity over the interval analyzed (e.g. Miyahara et al. 2004). This seeming contradiction between the results obtained here (cf. Mendoza 1997; Usoskin et al. 2001) and from ^{14}C data can be potentially reconciled in a view of the possible inversion of the cycle phase in the cosmic ray modulation during the periods of very weak activity like the MM (Owens et al. 2012). Thus, one or two cycles can be lost in the ^{14}C data, due to forward and then reverse phase shifts in the beginning and end of the Maunder minimum, leading to a seemingly extended cycles in ^{14}C data.

3.3. Sunspot numbers

On average, the fraction of active days observed during MM was low, below 0.4 in the triennial data (Fig. 4) for ML and MO models, except for the year 1666 (MO model) which is however based on a single observation, and reaching up to > 0.7 in the most conservative MS model. We note that, for the normal cycles, the active day fraction is about 100% except for the years around solar minimum (Kovaltsov et al. 2004; Vaquero et al. 2012, 2014). The value of F_A was never below 0.15 for annual and 0.29 for triennial (see Fig. 5) during the period 1850–1995. Accordingly, such low values F_A even for the peaks during the MM correspond to (or are lower than) the minimum state of modern solar cycles. Therefore, although a cyclic activity during the MM is clear, at least during the core period, the sunspot cycles were weak, with the maxima being comparable to the modern cycle minima. We note that high solar cycles of the magnitude 40-100 in sunspot number as proposed by Zolotova & Ponyavin (2015) would unavoidably imply $\approx$ 100% active day fraction (Vaquero et al. 2014) during most of the years, which contradicts with the data (cf. Fig. 2).

In order to assess the sunspot number R from the active day fraction F_A, we apply a method adopted from (Kovaltsov et al. 2004; Vaquero et al. 2012, 2014). For the annual data the relation was (Kovaltsov et al. 2004): $R = 19 \cdot F_A^{1.25}$ for $F_A \leq 0.5$ and $R = 2.1 \cdot \exp(2.69 \cdot F_A)$ for $0.5 < F_A \leq 0.8$. The relation between triennial values R and F_A is shown in Figure 5 for the period 1850–1995. One can see that the relation is quite good for $F_A <$

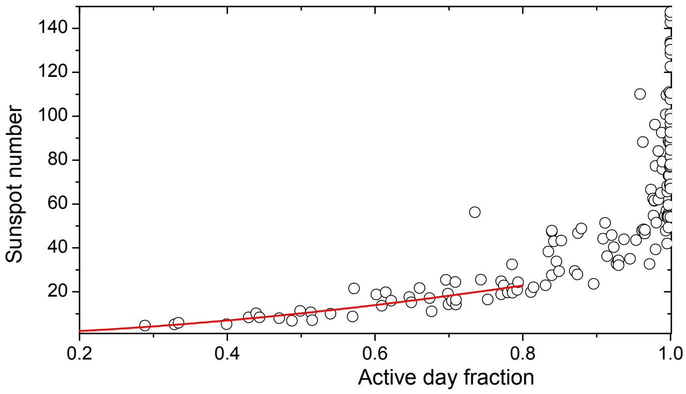

Fig. 5. Relation between triennial sunspot numbers and active day fraction for the period 1850–1995 using the Group Sunspot Number (Hoyt & Schatten 1998a). The red curve is the best fit relation $R = 33.6 \cdot F_A^{1.72}$.

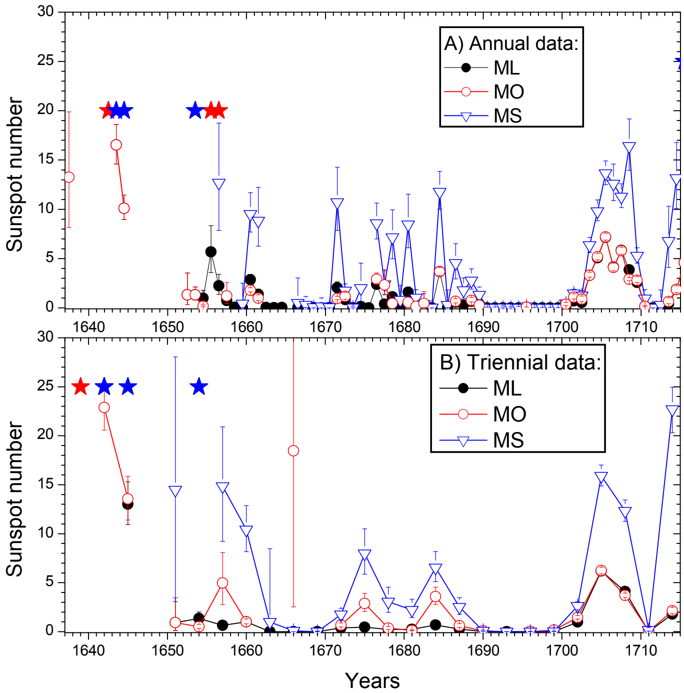

Fig. 6. Annual (panel A) and triennial (panel B) sunspot numbers reconstructed in the three models as denoted in the legends. Years with low statistics ($N_T < 10$) are not shown. Stars indicate that the sunspot number cannot be assessed from the active day fraction (see text) and is greater than 18/23 for the annual/triennial data.

0.8 (with the only outlier related to the period 1954–1956 which corresponded to the growth phase of the highest solar cycle #19) and can be well approximated by a dependence $R = 33.6 \cdot F_A^{1.72}$. The relations loosens for $F_A > 0.8$ and is lost completely with the active day fraction approaching unity. Thus, the active day fraction is a good index of sunspot activity until it reaches 0.8.

Using these dependencies we have evaluated the sunspot numbers during the period analyzed, as shown in Figure 6. One can see that the sunspot numbers appear below 2 during the deep MM (1645–1700) and 7 ca. 1705 in the least conservative model ML. The optimum MO model yields the sunspot number not exceeding 5 for the deep MM and 7 ca. 1705 (except for the very uncertain period ca. 1666 with the lack of observations). The most conservative MS model yields sunspot cycles below 10 during the core MM and a possible relatively high cycle in the 1650s, which is based on the lack of overlapping records from different observers, and about 15 ca. 1705. Anyway, even these very strict model suggests that the cycles were lower than 15–20 in sunspot numbers, which is much lower than the present cycle #24 and an order of magnitude lower than the very high cycles proposed by Zolotova & Ponyavin (2015). Considering the severe reduction of the statistics and a possible strong bias towards active days in the MS model, we believe it is not indicative for the true solar activity evolution during the MM and may represent only the uppermost upper (*maximum maximorum*) bound.

4. Conclusions

Using three models of different level of conservatism to treat generic "no-sunspot" statements, we have created a database of reliable sunspot observation around the Maunder minimum (1637-1715) and revised the sunspot cyclic activity over that period. We show that:

1. A large number of no-spot records, corresponding to the solar meridian observations, may be unreliable in the HS98 database.
2. The active day fraction remained low (below 0.3–0.4) throughout the MM, indicating the low level of sunspot activity.
3. The solar cycle appears clearly during the core MM with maxima at 1657, 1675, 1684, 1705 and possibly 1666.
4. The length of the solar cycle during the MM appears shorter (9 ± 1 years) in comparison with the standard 11-year solar cycle, but there is an uncertainty in that. A $\approx$ 20−year clustering of activity is also observed.
5. The magnitude of the sunspot cycle during MM is assessed to be below 5 (10 in the most conservative model) in sunspot numbers. The exact level is hardly possible to determine but it is below 10.
6. High solar cycles during the Maunder minimum, as proposed by Zolotova & Ponyavin (2015), contradict with the data.

We note that this is an uppermost upper (*maximum maximorum)* bound for solar activity during MM because of a possible selection bias (particularly important in the MS model), and the true level of activity may be smaller than that.

In any case, only a thorough review of each record and each solar observation during the MM can make it possible to reveal the best picture of solar activity during this period. Therefore, we encourage researchers (especially Latin scholars) to query and analyze the old texts to understand how the observations were made and the true level of solar activity they indicate.

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Table 1. Triennial statistics of sunspot day occurrence for the three models considered here (see text for definition). Columns are: #1 - central year of the triennial interval; #2 - number of active days N_A within the interval; #3, 7 and 11 - number of total observational days N_T considered in the three models, respectively; #4, 8 and 12 - lower 90% bound of the active day fraction, for the tree models, respectively; #5, 9 and 13 - median active day fraction, for the tree models, respectively; #6, 10 and 14 - upper 90% bound of the active day fraction, for the tree models, respectively.

		ML				MO				MS			
Year	N_A	N_T	F_{low}	F_{med}	F_{up}	N_T	F_{low}	F_{med}	F_{up}	N_T	F_{low}	F_{med}	F_{up}
1639	9	10	0.636	0.851	0.965	10	0.636	0.851	0.965	9	0.742	0.932	0.994
1642	135	137	0.956	0.980	0.992	168	0.752	0.800	0.843	106	0.956	0.980	0.992
1645	99	171	0.521	0.576	0.633	167	0.533	0.590	0.647	99	0.972	0.992	0.998
1648	0	0	N/A	N/A	N/A	0	N/A	N/A	N/A	0	N/A	N/A	N/A
1651	2	20	0.039	0.123	0.267	20	0.039	0.123	0.267	3	0.248	0.613	0.900
1654	31	201	0.120	0.154	0.195	355	0.068	0.087	0.109	33	0.827	0.921	0.974
1657	17	170	0.070	0.100	0.140	52	0.234	0.329	0.437	27	0.471	0.622	0.759
1660	66	499	0.114	0.131	0.151	501	0.114	0.131	0.150	130	0.439	0.506	0.573
1663	0	168	0	0.003	0.015	0	N/A	N/A	N/A	4	0.010	0.128	0.448
1666	1	320	0.001	0.003	0.011	1	0.223	0.706	0.974	48	0.006	0.032	0.089
1669	0	541	0	0	0.003	0	N/A	N/A	N/A	109	0	0.005	0.024
1672	47	625	0.064	0.074	0.086	459	0.086	0.101	0.121	262	0.148	0.179	0.215
1675	47	561	0.070	0.082	0.097	196	0.197	0.239	0.287	108	0.363	0.434	0.509
1678	30	538	0.045	0.055	0.068	415	0.057	0.071	0.089	121	0.193	0.248	0.312
1681	30	516	0.047	0.057	0.070	738	0.034	0.039	0.047	146	0.159	0.205	0.260
1684	72	683	0.093	0.104	0.116	264	0.235	0.272	0.312	186	0.334	0.386	0.440
1687	42	697	0.051	0.058	0.068	432	0.080	0.096	0.116	190	0.179	0.221	0.268
1690	12	839	0.011	0.013	0.016	362	0.022	0.032	0.047	374	0.022	0.031	0.046
1693	0	786	0	0	0.001	0	N/A	N/A	N/A	298	0	0.001	0.007
1696	4	944	0.004	0.004	0.005	311	0.006	0.013	0.025	534	0.004	0.006	0.012
1699	9	945	0.008	0.008	0.010	198	0.028	0.046	0.072	528	0.011	0.016	0.024
1702	122	935	0.123	0.129	0.136	752	0.150	0.161	0.174	535	0.206	0.226	0.248
1705	332	883	0.363	0.374	0.386	880	0.364	0.375	0.387	511	0.623	0.647	0.673
1708	252	852	0.283	0.294	0.306	903	0.268	0.278	0.288	450	0.530	0.558	0.587
1711	6	725	0.005	0.006	0.011	257	0.013	0.023	0.040	139	0.024	0.045	0.078
1714	128	698	0.169	0.182	0.196	631	0.185	0.201	0.219	160	0.746	0.796	0.841

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